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A new sky subtraction technique for low surface brightness data

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Abstract. We present a new approach to the sky subtraction for long-slit spectra suitable for low-surface brightness objects based on the controlled reconstruction of the night sky spectrum in the Fourier space using twilight or arc-line frames as references. It can be easily adopted for FLAMINGOS-type multi-slit data. Compared to existing sky subtraction algorithms, our technique is taking into account variations of the spectral line spread along the slit thus qualitatively improving the sky subtraction quality for extended targets. As an example, we show how the stellar metallicity and stellar velocity dispersion profiles in the outer disc of the spiral galaxy NGC5440 are affected by the sky subtraction quality. Our technique is used in the survey of early-type galaxies carried out at the Russian 6-m telescope, and it strongly increases the scientific potential of large amounts of long-slit data for nearby galaxies available in major data archives.

1. Introduction

Low-surface brightness ($\mu_B > 23$ mag/arcsec^2) outer regions of galaxies contain crucially important information for understanding the properties of their extended discs and dark matter haloes. Brightness profiles of dwarf early-type galaxies whose mean surface brightness is correlated with the luminosity, can be entirely in the low-surface brightness regime. Analysis of absorption line spectra at such surface brightness levels is often hampered by systematic errors of the sky subtraction that sometimes may lead to wrong astrophysical conclusions. Therefore, in order to analyse deep spectral data, it is important to improve the sky subtraction technique.

Here we present a new approach to the sky subtraction for long-slit spectra based on the controlled reconstruction of the night sky spectrum in the Fourier space using twilight or arc line frames as references.

Due to optical distortions, the shape of the spectral line spread function (LSF) in a long-slit spectrograph varies along the wavelength range as well as along the slit. In Fig. 1, we provide an example of the LSF shape of the SCORPIO (Afanasiev & Moiseev 2005) universal spectrograph at the Russian 6-m telescope reconstructed from the twilight frame (i.e. the Solar spectrum). The LSF is slightly asymmetrical and cannot be described by the Gaussian function, a usual parametrization in most data reduction packages. Here we use the Gauss-Hermite representation (van der Marel & Franx

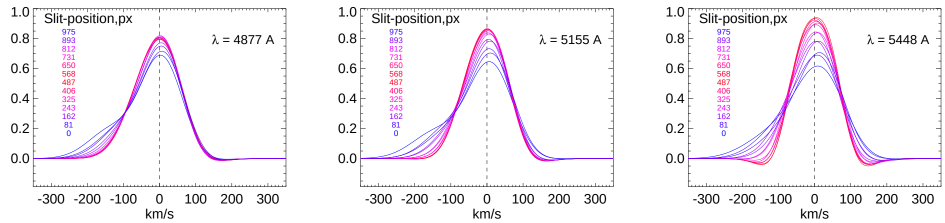

Figure 1. An example of the LSF shape of the SCORPIO reconstructed from the twilight frame at different wavelength and slit positions. We used the Gauss-Hermite LSF representation. One can see that the profile asymmetry increases towards the outer slit regions. There is also a notable change of the overall spectral resolution from blue to red.

1993) up-to the 4th order moment that allows one to describe first-order differences of the line profile from the Gaussian shape. These LSF variations affect the night sky spectrum which is subtracted from science frames during the data reduction. On the Fig. 2 we show a reduced long-slit spectrum of the spiral galaxy NGC 5440 before the sky subtraction step.

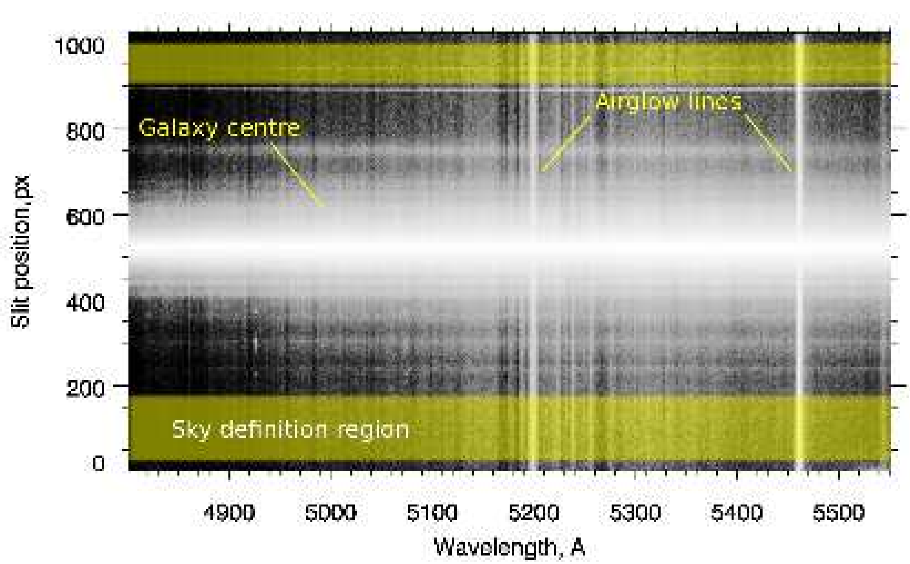

Figure 2. A reduced long-slit spectrum of the spiral galaxy NGC 5440 before the sky subtraction step. Yellow areas denote a region of the frame used to construct the night sky spectrum used for the sky subtraction. Taking into account the profile variation shown in Fig. 1, it is clear that the intrinsic LSF shape in these region will differ from that in regions of the galaxy closed to the slit centre.

2. The sky subtraction algorithm

In the traditional sky subtraction technique implemented in most standard data reduction packages (IRAF, MIDAS), the night sky spectrum is constructed from the outer regions of the slit which are (supposedly) free of the galaxy light as a κ-sigma clipped average. Then it is subtracted at every slit position.

The new algorithm presented here is an improvement of a method proposed in Chilingarian et al. (2009) aimed at increasing its stability with certain features taken from the technique by Kelson (2003). However, compared to the latter method, our approach allows one to take into account empirically the variations of the LSF along the slit.

The new technique includes several steps:

1. An oversampled sky spectrum is created from the non-linearized spectra using the wavelength solutions in order to perform the pixel-to-wavelength coordinate mapping. Then it is approximated using a b-spline. This approach was proposed by Kelson (2003) to improve the sky subtraction in undersampled datasets.

2. At every position along the slit, we change the LSF shape inside this night sky spectrum using a Fourier-based technique into the LSF at that slit position. The observed sky spectrum is a convolution of a true spectrum with the LSF:

$$R(\lambda, y) = R_0(\lambda) * LSF(\lambda, y); \quad S(\lambda, y) = S_0(\lambda) * LSF(\lambda, y), \tag{1}$$

   where $R(\lambda, y)$ is a template spectrum (high signal-to-noise twilight frame), $S(\lambda)$ – the night sky spectrum. Then according to the convolution theorem the ratio between the Fourier transforms of the template spectrum and the object spectrum is a constant function on position along slit y:

$$\frac{FFT(S(\lambda, y))}{FFT(R(\lambda, y))} = \frac{FFT(S_0(\lambda))}{FFT(R_0(\lambda))} = \frac{FFT(S(\widetilde{y}, \lambda))}{FFT(R(\widetilde{y}, \lambda))} = F(\lambda), \tag{2}$$

   where $\widetilde{y}$ – position at the sky definition region. The night sky spectrum at current position along slit can be expressed as follows:

$$S(y, \lambda) = FFT^{-1}\left(\frac{FFT(S(\widetilde{y}, \lambda))}{FFT(R(\widetilde{y}, \lambda))} \cdot FFT(R(y, \lambda))\right). \tag{3}$$

3. The *b*-spline parametrization provides the necessary regularisation for the numerical stability of this procedure.

3. Usage example and perspectives of the method

In Fig. 3 we present the result of the data analysis of a long-slit spectrum of NGC 5440 for the two sky subtraction techniques. We fitted the reduced sky subtracted spectra with high resolution stellar population models with the NBURSTS full spectral fitting technique (Chilingarian et al. 2007b,a) and extracted kinematical (radial velocity and velocity dispersion) and stellar population (age and metallicity) parameters along the slit. The radial profiles of velocity dispersion and metallicity are shown in Fig. 3. While

the measurements are very similar near the galaxy centre, they differ notably in the peripheral regions. With the new sky subtraction technique the uncertainties are lower, and the general trend of the galaxy metallicity gradient correspond to the physical expectations. The traditional sky subtraction technique possesses systematic errors in the low surface brightness regime, which propagate to the data analysis and may result in misleading astrophysical conclusions.

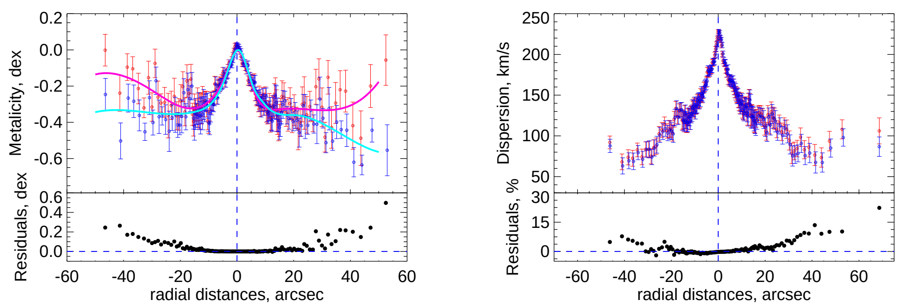

Figure 3. Comparison between traditional technique and our deconvolution. The two left panels display the internal velocity dispersion profiles of NGC 5440. Blue data points are for the new technique, while red ones are for the “classical approach”. Differences between the two approaches are displayed in the bottom panel. The two right panels display the stellar metallicity profiles of NGC 5440 using the same symbols and colours as on the left panels.

Our sky subtraction technique is adopted in the survey of nearby lenticular galaxies (P.I.: prof. Zasov, Moscow State University) carried out at the Russian 6-m telescope using the SCOPRIO spectrograph. Our approach can be easily modified for multi-slit spectroscopic data with parallel slits (“FLAMINGOS”-type spectra).

Since out technique improves the quality of data analysis at low signal-to-noise ratios, it can also be used to re-reduce and re-analyse long-slit spectroscopic datasets for hundreds of galaxies obtained with different telescopes and publicly available in data archives.

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